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THE POSSIBILITY OF USING MICROWAVE IONIZATION TO OBTAIN NONEQUILIBRIUM PLASMA IN MHD GENERATORS

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THE POSSIBILITY OF USING MICROWAVE IONIZATION TO OBTAIN NONEQUILIBRIUM PLASMA IN MHD GENERATORS

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ABSTRACT. The possibility of creating high-conductivity, nonequilibrium plasma at low gas temperature is pointed out. The plasma can be used in MHD generators. Microwave plasma conductivity in excess of 100 mohms/m can be obtained in argon without alkali metal admixtures. Estimates are given for the efficiency of use of this preliminary ionizer in MHD devices. Data obtained are compared with experimental results using electron flow as the preliminary ionizer in MHD generators.

Interest in the problem of using an electrically conducting gas as the working substance in engines, or in propulsion plants, is a recent development. /705*

The electrical conductivity of the plasma in a generator should be increased significantly as compared with equilibrium conditions in order that the specific power of a magnetohydrodynamic (MHD) generator be high at relatively low gas temperatures (~1500°K).

Today, intensive study is being made of the possibility of increasing the conductivity of the working substance in MHD installations by using a thermally nonequilibrium plasma in which electron temperature is high enough to effectively ionize the atoms of gas at a relatively low gas temperature [1-5]. Various methods of preliminary ionization, such as photoelectric ionization, radioactive ionization, ionization by electron flows glow discharge, high-frequency discharge, incomplete discharge, and the like, have been suggested to obtain nonequilibrium plasma in MHD generators, in addition to using self-induced fields for this purpose. Without dwelling on detail on the advantages, and disadvantages, of the methods mentioned for creating a nonequilibrium plasma, let us point out that the problem of obtaining effective preliminary ionization has not yet been solved.

This paper is devoted to ascertaining the possibilities of using electro-

* Numbers in the margin indicate pagination in the foreign text.

magnetic fields in the superhigh-frequency (SHF) range to create thermally non-equilibrium plasma with a high degree of conductivity at low gas temperature, and to evaluate the desirability of using it in MHD devices. (The primary results of this report were presented to the Presidium of the Academy of Sciences of the Ukrainian SSR in June 1970).

Results of Experimental Investigations

A number of papers have been written [6-9] on the feasibility of using alternating electromagnetic fields with frequencies in the meter wavelengths for preliminary ionization in MHD generators. This method of forming a nonequilibrium plasma has certain advantages over other of the known methods for so doing. These papers indicated the obtaining of nonequilibrium plasma with quite good /706 conductivity (reference [7], for example, cites a figure of over 2,000 mhos per meter). However, preliminary ionization by high-frequency fields does have significant drawbacks, despite its seeming effectiveness. Specifically, the application of a high-frequency ionizing field to the main excitation field causes the phenomenon known as generator cutoff [7]. Moreover, only a part of the power available from the generators operating in the frequency ranges used by the authors was expended on ionizing the gas [9].

It has been shown that the properties of a plasma excited in rapidly alternating electromagnetic fields depend on the frequency of the exciting field [10], and that wehn a transition is made to superhigh frequencies it is possible to find conditions for creating cold plasma (SHF arc) at a low gas temperature and a low level of power consumption [11].

On the other hand, references [12, 13] indicate that the excitation of plasma by an SHF discharge is associated with the appearance of plasma, accompanied by the formation of a high concentration of charged particles in the plasma, and increasing with the increase in the frequency of the SHF field. Moreover, the SHF discharge can provide virtually complete absorption of the plasma's power input, as distinguished from the effect of a high-frequency gas discharge, as we know [14].

So it is of interest to find conditions for the excitation of elongated volumes of thermally nonequilibrium plasma from an SHF discharge combining the useful features noted for the particular plasma, namely, high concentrations of charged particles (responsible for its conductivity) at a low power consumption level and low gas temperature. The properties of a plasma excited by a continuous duty, 3-cm generator in an atmosphere of inert gases were investigated for this purpose. (The possibility, in principle, of obtaining thermally nonequilibrium plasma at elevated gas pressures in the decimeter band by using high pulse fields in resonators is pointed out in [15]).

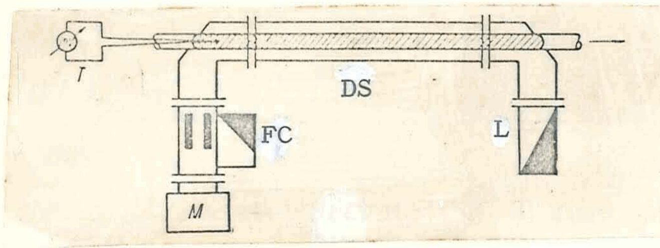
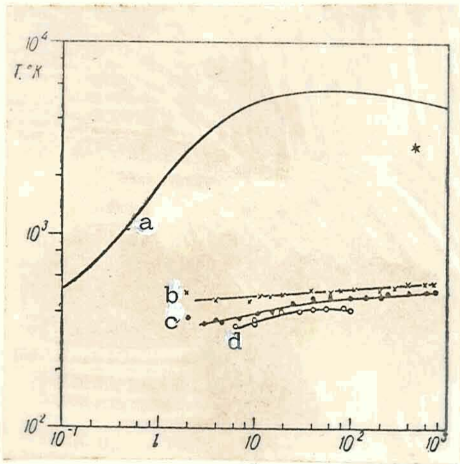


Figure 1

Figure 1 shows the schematic arrangement of a device for obtaining SHF plasma, and for measuring the temperature of the gas in the plasma, as well as the magnitude of the microwave power expended to form the plasma. The microwave power exciting the gas discharge is supplied to the discharge section, DS, from a magnetron generator, M, through a ferrite circulator, FC. The waveguide, 23 x 10 mm in section, terminates in matching load L. The quartz discharge tube is connected to the high-vacuum system and the gas bottles on the side shown by the arrow in the figure.

Gas temperature is measured by a tungsten-rhenium (W-Re) thermocouple, T (wire diameter 0.1 mm), vacuum sealed where it enters the quartz tube containing the plasma. (Spectral investigations of the SHF plasma revealed that the temperature of the gas in the plasma was so low that the known optimal method of measuring gas temperature by the forbidden structure of molecular bands cannot be used [16]). The microwave power expended to form the plasma was found by the calorimetric method. /707

The investigations revealed that a limited volume of plasma, the magnitude of which will depend on the nature of the gas, can be excited in a discharge tube for given microwave power and gas pressure. There is an optimal pressure for each of the gases studied (argon, neon, and helium) in the 10 to 40 torr range at which the excited plasma has maximum sizes. The length of the plasma column increases with increase in microwave power until the tube in the waveguide is completely full, and this is true for all gases used. Microwave power expended is between 10 and 60 watts per cubic centimeter of plasma.



ρ, mm Hg

Figure 2

Figure 2 (b, c, d) shows the temperature of the plasma in terms of the Ar, Ne, and He pressures in a system in which the value of the microwave power input is fixed. Under these conditions, in the pressure range from 10 to 500 torrs, and in the case of Ar and Ne, the plasma fills the entire volume of the discharge tube in the waveguide (length 75 mm, inside diameter 2.8 mm).

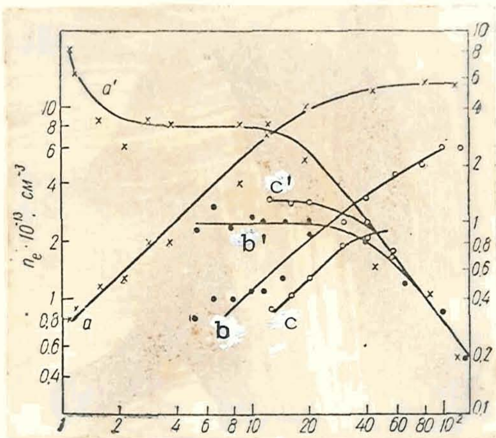
This same figure contains the curve marked a, used for purposes of comparison, and taken from reference [17], to show the temperature of the gas in a direct current arc in mercury vapors. The * indicates the temperature of the gas in a direct current arc in argon when $n_e \sim 10^{15} cm^{-3}$, and is taken from reference [16]. As we see, in an SHF plasma the temperature of the gas in the range of pressures studied has practically no dependence on the nature of the gas, or its pressure, and is much lower than the temperature of the gas from a direct current arc.

A thin-walled (outside diameter 0.2 mm) glass capillary tube was inserted in the plasma in place of the thermocouple to make control checks of the temperature of the gas in an SHF discharge. Excitation of the SHF plasma in a system with a capillary tube at p = 100 torrs over a long period of time failed to melt the tube, indicative of the fact that the temperature of the gas in the plasma under these conditions was lower than the melting point of the glass, that is, below 900°K.

Conductivity of the plasma considered was evaluated by measuring the electron concentration, n_e, and the frequency of collisions between the electrons and the atoms of the gas, v_{cg}, [cg - collisions in the gas] in the plasma. The n_e and /708

v_{cg} values were found by the microwave method of probing the plasma in a waveguide, suggested and developed in references [18, 19] for studying a direct current discharge.

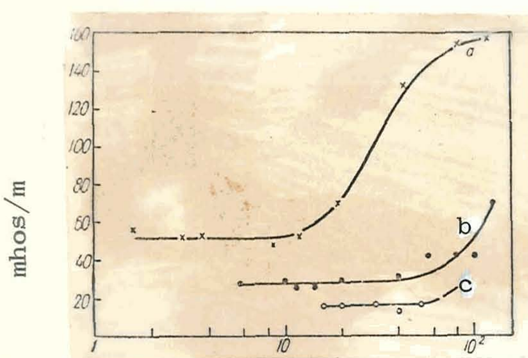
What this method amounts to is the utilization of the reaction between the electrical parameters of the plasma under study (n_3, v_{cg}) and the characteristics of the probing signal of a selected frequency passed through this plasma. Reference [20] pointed to the possibility of using this method to study the parameters of an SHF discharge.



p, torr

Figure 3

Figure 3 shows the concentration of electrons and the frequency of collisions of electrons with the atoms of the gas, $v_{cg}p$, in an SHF plasma in terms of argon (a and a'), neon (b and b'), and helium (c and c') pressures for the powers dissipated in unit volume of plasma close to those at which the temperature of the gas in the plasma was measured. As we see, given the conditions under which the investigations were made, the plasma forms with a high concentration of charged particles and increases monotonically with rise in pressure. The increase in the magnitude of n_e slows somewhat in the high pressure region.



ρ, mm, Hg

Figure 4

The relationships in Figure 3 were used to evaluate the conductivity of an SHF plasma. Figure 4 shows the results. Conductivity of an SHF plasma is high over the entire range of gas pressures investigated. Significantly, in this case the high conductivity is obtained without the addition of readily ionizable "additives". The microwave power expended to form the plasma is low (10 to 60 watts per cubic centimeter).

We should point out that in the case of a moving plasma the velocity of the gas is about 1,000 m/s, and this evidently has no real effect on the plasma parameter measurements we made because in this case the time the gas remains in the region of the charged chamber still will be much longer than the time required to establish the steady state condition in a nonequilibrium SHF plasma [13].

Discussion of Results. Conclusions.

The investigations show that it is possible, in principle, to obtain thermally nonequilibrium plasma with a high degree of conductivity at low gas temperature by using microwave ionization. This, naturally enough, raises the question of whether or not we can build an MHD generator capable of functioning on nonequilibrium plasma obtained in this manner.

Let us make certain assessments as to the effectiveness of the use of preliminary microwave ionization in MHD devices and compare the results obtained with data from one of the known preliminary ionization methods. First of all, let us ascertain if we can, or cannot, provide the conditions whereby the energy expended on forming the nonequilibrium plasma with microwaves will be less than the energy generated by the MHD generator. Let us compare the data with the results contained in reference [5], which took up the method of creating nonequilibrium ionization by using an electron flow.

We shall, just as did reference [5], take the magnitude of the rate of flow /709 of plasma as equal to 470 m/s, and the magnetic induction as 50,000 gausses. Then, recognizing that the electron flow in [5] resulted in a plasma conductivity of 6 mhos/m, and that the microwaves in our case provided between 10 and 160 mhos/m, we obtain the following specific power ratings for MHD devices: ionization by electron flow $P = 5$ watts/cm^3; SHF ionization $P = 8$ to 130 watts/cm^3.

Thus, we can obtain an adequately high value for the specific power of MHD generators with preliminary SHF ionization without recourse to expensive alkali "additives".

The power expended to form a nonequilibrium plasma by the electron flow in [5] was about 30 watts/cm^3, but as the authors say, this magnitude can be reduced to 0.04 watts/cm^e. In our case the formation of cold microwave plasma with high conductivity (SHF arc) requires the expenditure of between 30 and 180 watts/cm^3 of power, with the efficiency of the continuous duty magnetron generator (30%)

taken into consideration. Although this magnitude is much smaller than the power required to form and maintain the thermally equilibrium plasma of a direct current arc, the expenditures on preliminary ionization are approximately equal to the MHD generator output power.

Two significant facts should be pointed out, however. The current investigations did not include the task of finding the minimum power needed for the operation of a preliminary SHF ionizer, so the continuous duty mode of operation of the microwave generator for the case of lack of any noticeable initial ionization was used. And it is clear that this preliminary ionization method will be the more effective if the microwave power is supplied from a pulse source with a pulse length adequate for reaching the specified ionization level, rather than being supplied from a continuous source of oscillations. Then, when the efficiency of the SHF pulse devices is 70 percent, and when the pulse length is about 1 μs, corresponding to the establishment of a steady-state condition for the SHF plasma [13], for a duty factor of 10, the power consumed in preliminary ionization can be reduced from 30 to 180 to 1.5 to 9 watts/cm^3.

Moreover, when microwave radiation is used to increase the conductivity of plasma with a temperature of 1500°K in MHD device models, the initial ionization will be high enough to result in some reduction in the power expended on preliminary ionization. There are, at this time, reports that the application of powerful SHF radiation to the front of a shock wave results in the appearance of an ionization front that changes the concentration of charged particles in the plasma, so that the required microwave power in this case is less than that needed to break down the gas [21].

	Ionization by electron beam [5]	Ionization by microwave generator
Magnetic field, oersteds	50,000	50,000
Rate of flow, m/s	470	470
Gas temperature, °K	1,500	less than 1000
Working substance	Argon with Cs "additive"	Ar
Electrical conductivity of gas, mhos/m	6	10 - 160

	Ionization by electron beam [5]	Ionization by microwave generator
Designed specific power of MHD generator, watts/cm^3	5	8 - 130
Minimum power needed for preliminary ionization, watts/cm^3	0.04	1.5 - 9

The above table lists the principle results of the calculations made to /710 evaluate the possibilities of using preliminary SHF ionizers in MHD generators, so they could be compared with the data listed in reference [5]. The results are such that one can be hopeful about the great possibilities of using nonequilibrium plasma obtained by microwave ionization in MHD devices. At the same time, it must be recognized that the results set forth above are at best approximations of what can take place in working models of MHD devices.

It seems to us that the evaluations made point to the desirability of continuing the work only these lines with models of MHD generators.

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REFERENCES

1. Rosa, R. J., Proc. IEEE, 51, 1963, p. 774.

2. Voshall, R. J., Emmerich, W. S., IEEE Trans. Aerospace, 2, 1964, p. 807.

3. Kerrebrock, J. Z., AIAA, J. 3, No. 4, 1965.

4. Haines, M. J., Mc Nab, J. R., Proc. IEEE, 56, 1968, p. 1476.

5. Shair, F. H., Sherman, A., Prikladnaya magnitnaya digro- i gazodinamika [Applied Magnetic Hydro- and Gas-Dynamics], "Nauka," Moscow, 1968, p.9.

6. Gourdine, M. C., Larsen, H. M., Dresser, D. L., SAE J., 71, 1963, p. 58.

7. Gourdine, M. C., MGD-generatory elektricheskoy energii (Trudy simpoziuma v N'yukasle) [MHD Generators of Electric Energy (Proceedings of the Newcastle Symposium)], VINITI, Moscow, 1963, O. 224.

8. Polk, D. H., PPTE, 4 (33), 1965, p. 13.

9. Dworschak, J. R., Brandmaier, H. E., AIAA J., 10, 1968, p. 2021.

10. Motornenko, A. P., Truten', I. D., Opt. i. spektr., 17, 1964, p. 628; Motornenko, A. P., Opt. i. spektr., 23, 1967, p. 528.

11. Motornenko, A. P., Martynyuk, S. P., UFZh, 12, 1967, p. 754; 15, No. 9, 1970.

12. Maksimov, A. I., Pis'ma v ZhETF [Letters to the Editor of ZhETF], 2, 1965, p. 216.

13. Motornenko, A. P., Belousov, Ye. V., Zin'ko, N. S., UFZh, 12, 1967, p. 1773.

14. Obrazovaniye i stabilizatsiya svobodnykh radikalov [Formation and Stabilization of Free Radicals], Moscow, IL, 1962.

15. Chernetskiy, A. V., Doktorskaya dissertatsiya [Doctoral Dissertation], Moscow, Soyuznyy NII priborostroyeniya [Union Scientific Research Institute of Instrument Building], 1967.

16. Kolesnikov, V. N., Trudy Fiz. in-ta im. Lebedeva, 30, 1964, p. 66.

17. Elenbaass, W., The High Pressure Mercury Vapour Discharge, Amsterdam, 1951.

18. Takeda, S., Japan J. Appl. Phys., 2, 1963, p.58.

19. Plyuta, V. Ye., DAN BSSR, 9, 1967, p. 786; 12, 1968, p. 111.

20. Belousov, Ye. V., Motornenko, A. P., Trudy conferentsii po elektronnoy tekhnike. Iskrovyye razryadniki i gazorazryadnyye pribory SVCh [Proceedings of the Conference on Electronic Engineering. Spark Dischargers and Superhigh-Frequency

Gas-Discharge Instruments], Moscow, In-t "Elektronika," No. 2 (18), 1970, p. 89.

21. Bethke, G. W., Ruess, A. D., PPTE, 7, 1970, p. 16.

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